A Proposed Framework for Network-Centric Maritime Warfare Analysis

Ralph S. Klingbeil
Keith M. Sullivan
Undersea Warfare Analysis Department

NAVSEA
NEWPORT
Undersea Warfare Center Division

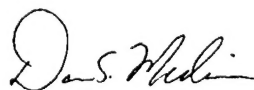# Naval Undersea Warfare Center Division
Newport, Rhode Island

20030905 097

PREFACE

This report was funded under NUWC Project No. 760B250.

The technical reviewer for this report was Jeffrey C. Fisher (Code 60D).

Reviewed and Approved: 15 July 2003

David S. Medeiros
Head, Undersea Warfare Analysis Department

REPORT DOCUMENTATION PAGE

Public reporting for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 15 July 2003	3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE

A Proposed Framework for Network-Centric Maritime Warfare Analysis

5. FUNDING NUMBERS

6. AUTHOR(S)

Ralph S. Klingbeil
Keith M. Sullivan

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Undersea Warfare Center Division
1176 Howell Street
Newport, RI 02841-1708

8. PERFORMING ORGANIZATION REPORT NUMBER

TR 11,447

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The benefits of network-centric warfare are addressed in many publications, but few of these publications actually demonstrate how to quantify these alleged benefits. This report proposes an analytical framework to quantify the value-added of network-centric warfare; that framework is queueing theory, which is based on the concept of a demand-for-service process. Most warfare tasks can be characterized as demand-for-service processes. This report shows how queueing theory can be applied to demand-for-service warfare tasks and thus provide the basis for analyzing and quantifying those tasks. In addition, this report demonstrates how the functions of many of the independent and dependent variables and associated warfare metrics can be translated into the characteristics and metrics of queues.

14. SUBJECT TERMS		15. NUMBER OF PAGES
Queueing Theory Network-Centric Warfare		18
		16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

A PROPOSED FRAMEWORK FOR NETWORK-CENTRIC MARITIME WARFARE ANALYSIS

INTRODUCTION

Network-centric warfare (NCW) is said to be "an information superiority-enabled concept of operations that generates increased combat power by networking sensors, decision makers, and shooters to achieve shared awareness, increased speed (and accuracy) of command, higher tempo of operations, greater lethality, increased survivability, and a degree of self-synchronization."[1]

In recent years, numerous publications have promoted the benefits of NCW, but most provide no quantification. This report proposes an analytical framework to quantify the value-added of NCW. While it is suspected that information technology and improved communications networks will increase combat effectiveness, the value-added of NCW could be negative (for example, data overload could confuse a war fighter and lead to incorrect decisions or long delay times). Military decision-makers need quantitative analyses of NCW so that they can make intelligent search and acquisition decisions.

Queueing theory presents a useful framework for analyzing some aspects of both NCW and platform-centric warfare (PCW). Most warfare tasks are characterized as demand-for-service processes, and queueing theory is ideal for analyzing such processes.

QUEUEING THEORY AS A WARFARE ANALYSIS FRAMEWORK

In 1909, A. K. Erlang developed queueing theory to analyze a demand-for-service system, namely, telephone switchboards. While warfare differs from telephone calls, the basic idea is the same: there are "customers" who demand "service." For example, incoming messages demand action by a decision-maker, sonar contacts demand attention from an operator, and targets demand the application of weapons.

Queueing theory (tandem queues with search for customers by multiple parallel, heterogeneous servers with balking, reneging, priorities, misclassifications, nonlinear feedback, etc.) provides a framework for the analysis and quantification of military systems and operations that can be characterized as demand for service. Such military systems and operations (and their associated systems) include antiair warfare (including fighter interception and cruise missile defense); strike; self-protection; command and control (including networks); intelligence, surveillance, and reconnaissance antisubmarine warfare; and maritime interception operations. In all of these warfare tasks, the concept of customers waiting for service applies. In addition, the functions of many of the independent and dependent variables and associated warfare metrics can be translated into the characteristics and metrics of queues.

Analysis of warfare tasks can involve complicated queues. Prioritization of sensor contacts, multiple tandem queues, and unusual probability distributions are a few of the complications that can arise during investigation. All of these problems, however, can be surmounted either through analytical formulas or through computer simulation.

The use of queueing theory requires modeling each of the queueing characteristics and pertinent structures for the systems and warfare tasks of interest. Inputs into the queueing model can require extensive modeling and/or data analysis.

Queueing theory terminology requires some interpretation for warfare applications. Seven characteristics are used to describe warfare and queueing theory: (1) arrival pattern, (2) service pattern, (3) loss processes, (4) queue discipline, (5) system capacity, (6) service channels, and (7) service stages.[2] Figure 1 describes these characteristics, each of which has a warfare equivalent. The relationship depends on the particular warfare task.

4. Queue Discipline describes how a customer is selected for service once in queue (FIFO, priorities, etc.)

5. System Capacity is the maximum size of a queue; finite or infinite

2. Service Pattern is described by service rate or service time

1. Arrival Pattern describes the input to the queueing system and is typically specified by arrival rate or interarrival time

PRIORITY

SERVER(S)

ARRIVALS

QUEUE

DEPARTURES

● TOI

◉ Non-TOI

BALK

RENEGE

6. Service Channels are the number of elements available to provide a given function

7. Service Stages are the set of end-to-end processes for completion of service

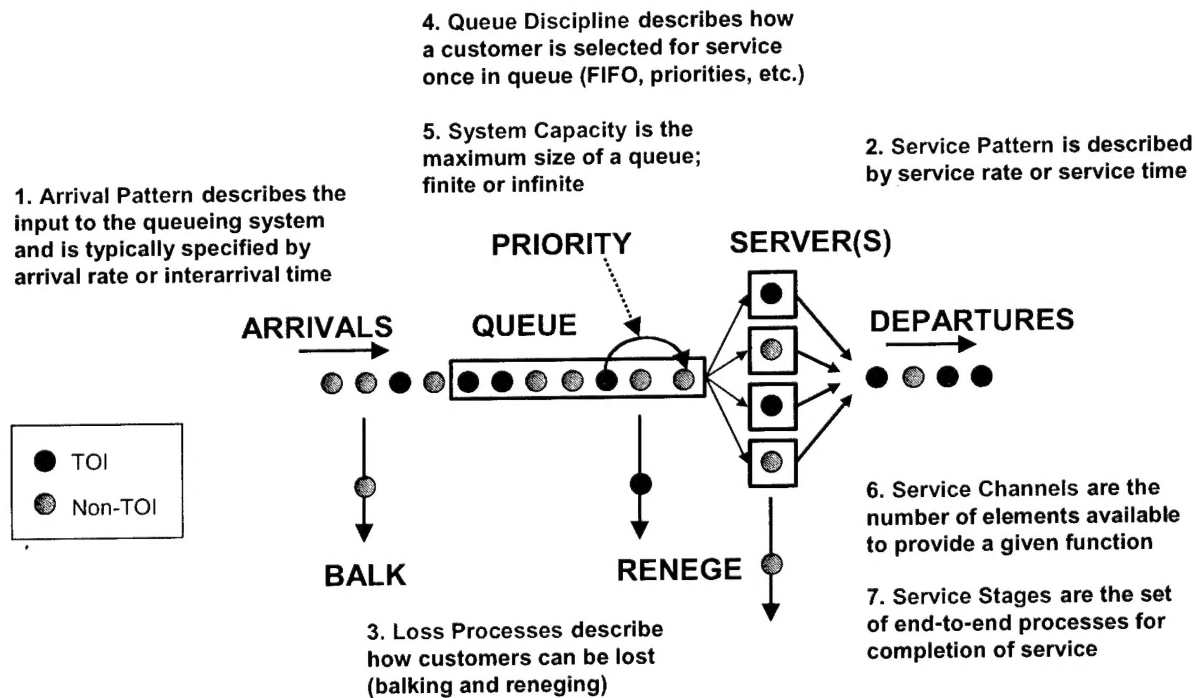3. Loss Processes describe how customers can be lost (balking and reneging)

Figure 1. Description of a Queueing System (TOI = Targets of Interest)

Many warfare tasks and enablers are amenable to analysis via queueing theory. Some of the warfare areas where queueing theory could be applied to quantify the benefits of NCW are

1. antisubmarine warfare (ASW) and antisurface warfare (ASUW),
2. self-protection against torpedoes and cruise missiles,

3. strike – fixed, mobile, and time-urgent targets,

4. special operations forces (SOF) (many SOF jobs, but not many SOF units),

5. intelligence, surveillance, and reconnaissance (ISR),

6. mine detection and avoidance (MDA),

7. command and control (C^2) and decision-making,

8. communications, and

9. maritime interception operations (MIO).

For these warfare tasks and enablers, tables 1 through 9 show one possible connection between warfare and queueing theory concepts.

Table 1. Example of ASW/ASUW Interpretation of Queueing Characteristics

Queueing System Characteristic	Warfare Equivalent
Arrival Pattern	Targets, interfering objects, system-generated false contacts
Service Pattern	Contact prosecution process based on classification decision
Loss Process	Detection threshold selection (balking); Contact moves out of sensor coverage (reneging)
Queue Discipline	Prioritization of sensor contacts for prosecution
System Capacity	Maximum number of contacts managed at a given time
Service Channels	Number of elements available for a given function
Service Stages	Set of end-to-end ASW/ASUW stages (search, localization, prosecution)

Table 2. Example of Self-Protection Interpretation of Queueing Characteristics

Queueing System Characteristic	Warfare Equivalent
Arrival Pattern	Number and types of weapons attacking own-force elements per unit time
Service Pattern	Contact prosecution process based on threat-risk decision and defensive system capability
Loss Process	Saturation of defensive systems (balking); Weapon poses no threat to self (reneging)
Queue Discipline	Prioritization of incoming weapons for defensive mechanism
System Capacity	Maximum number of weapons managed at a given time
Service Channels	Number of elements available for a given defensive function
Service Stages	Set of end-to-end self-defense stages (search, localization, weapon assignment, and launch)

Table 3. Example of Strike Interpretation of Queueing Characteristics

Queueing System Characteristic	Warfare Equivalent
Arrival Pattern	Desired number of targets to be destroyed in a given time
Service Pattern	Contact prosecution process based on target value and resource capability and availability
Loss Process	Target richness (balking); Target warning, mobility, or transience (reneging)
Queue Discipline	Prioritization of targets based on target value and resource capability and availability
System Capacity	Maximum number of targets that can be attacked at a given time
Service Channels	Number of elements available for a given strike function
Service Stages	Set of end-to-end strike stages (search, localization, resource assignment, and launch)

Table 4. Example of SOF Interpretation of Queueing Characteristics

Queueing System Characteristic	Warfare Equivalent
Arrival Pattern	Number of SOF missions per unit time
Service Pattern	Assignments based on mission value and resource capability and availability
Loss Process	Mission richness (balking); Target warning, mobility, or transience (reneging)
Queue Discipline	Prioritization of missions based on value and resource capability and availability
System Capacity	Maximum number of missions that can be undertaken at a given time
Service Channels	Number of elements available for a given set of SOF missions
Service Stages	Set of end-to-end SOF stages

Table 5. Example of ISR Interpretation of Queueing Characteristics

Queueing System Characteristic	Warfare Equivalent
Arrival Pattern	Number of ISR missions per unit time
Service Pattern	Assignments based on ISR mission value, resource capability, and availability
Loss Process	ISR mission richness (balking); Target warning, mobility, transience, or sensor coverage (reneging)
Queue Discipline	Prioritization of missions based on ISR value and resource capability and availability
System Capacity	Maximum number of ISR missions that can be undertaken at a given time
Service Channels	Number of elements available for a given set of ISR missions
Service Stages	Set of end-to-end ISR stages

4

Table 6. Example of MDA Interpretation of Queueing Characteristics

Queueing System Characteristic	Warfare Equivalent
Arrival Pattern	Mines, interfering objects (non-mine bottom objects), system-generated false contacts
Service Pattern	Contact management process based on detection and classification, decision and risk assessment
Loss Process	Detection threshold selection (balking); Object passes out of sensor coverage (reneging)
Queue Discipline	First come, first served (batch processing)
System Capacity	Maximum number of contacts managed at a given time
Service Channels	Number of elements available for a given function
Service Stages	Set of end-to-end MDA stages (search, localization, avoidance)

Table 7. Example of C^2 and Decision-Making Interpretation of Queueing Characteristics

Queueing System Characteristic	Warfare Equivalent
Arrival Pattern	Reports and requests per unit time
Service Pattern	Decisions per unit time
Loss Process	Saturation (balking); Perishability of the event (reneging)
Queue Discipline	First come, first served with priorities
System Capacity	Maximum number of decision-making tasks that can be handled
Service Channels	Usually one
Service Stages	Set of end-to-end decision-making stages

Table 8. Example of Communications Interpretation of Queueing Characteristics

Queueing System Characteristic	Warfare Equivalent
Arrival Pattern	Incoming messages and messages to be sent per unit time
Service Pattern	Processing messages per unit time
Loss Process	Overflow, jamming, path reliability (balking); Perishability of the message (reneging)
Queue Discipline	First come, first served with priorities
System Capacity	Maximum number of messages that can be successfully handled
Service Channels	Number of elements handling incoming messages
Service Stages	Set of end-to-end message handling stages

Note: Graph theory can be applied to the multiple path and path reliability problem.

Table 9. *Example of MIO Interpretation of Queueing Characteristics*

Queueing System Characteristic	Warfare Equivalent
Arrival Pattern	Arrival of benign and contraband ships to the operating area
Service Pattern	Interception process based on classification decision
Loss Process	Saturation of interception vessels (balking); Potential contraband vessel moving out of interception range (reneging)
Queue Discipline	Prioritization for interception
System Capacity	Maximum number of contraband vessels managed per unit time
Service Channels	Number of vessels available to do interception
Service Stages	Set of end-to-end interception processes (surveillance, search, detection, query, approach, board, divert, escort)

Many metrics can be used to quantify a queueing system. The following metrics were found to be the most useful metrics for this research:

1. probability that a customer acquires service (probability of acquisition), and

2. mean time that a customer waits in the queue until service begins.

Assuming exponential probability distribution functions for the arrival, service, and renege rates, the probability of acquisition and waiting time in the queue can be expressed in closed form. The derivation of formulas for probability of acquisition and waiting time in the queue is addressed by Sullivan and Grivell.[3]

NETWORK-CENTRIC WARFARE

Cebrowski and Garstka[4] developed a logical model for NCW based on the merging of three grids: information, sensor, and engagement (figure 2). The information grid provides the computer/communication backplane and is the entry fee for NCW; it also enables the operational architectures of the sensor and engagement grids. The sensor grid quickly generates battlespace awareness and synchronizes awareness with battlespace operations. The engagement grid exploits this awareness and translates it into combat power. The integration and interoperability of these grids are crucial to the success of NCW.

The U.S. Navy currently employs this model for its cooperative engagement capability, which combines a high-performance sensor grid with a high-performance engagement grid. The sensor grid fuses data from multiple sensors to develop a composite track with engagement quality, thus creating a high probability of successful engagement.

For analytical purposes, each box in figure 2 is a queue. Thus, the logical model can characterized as a system of queues where the departures from one queue are arrivals to another

(both forward and backward). In particular, the model is a queueing network that handles feedback (possibly nonlinear) and handles parallel, networked systems. This logical model can be classified as a demand-for-service system. Each box must handle incoming information and act upon that information (that is, incoming information demands actions by the sensors, deciders, and/or effectors).
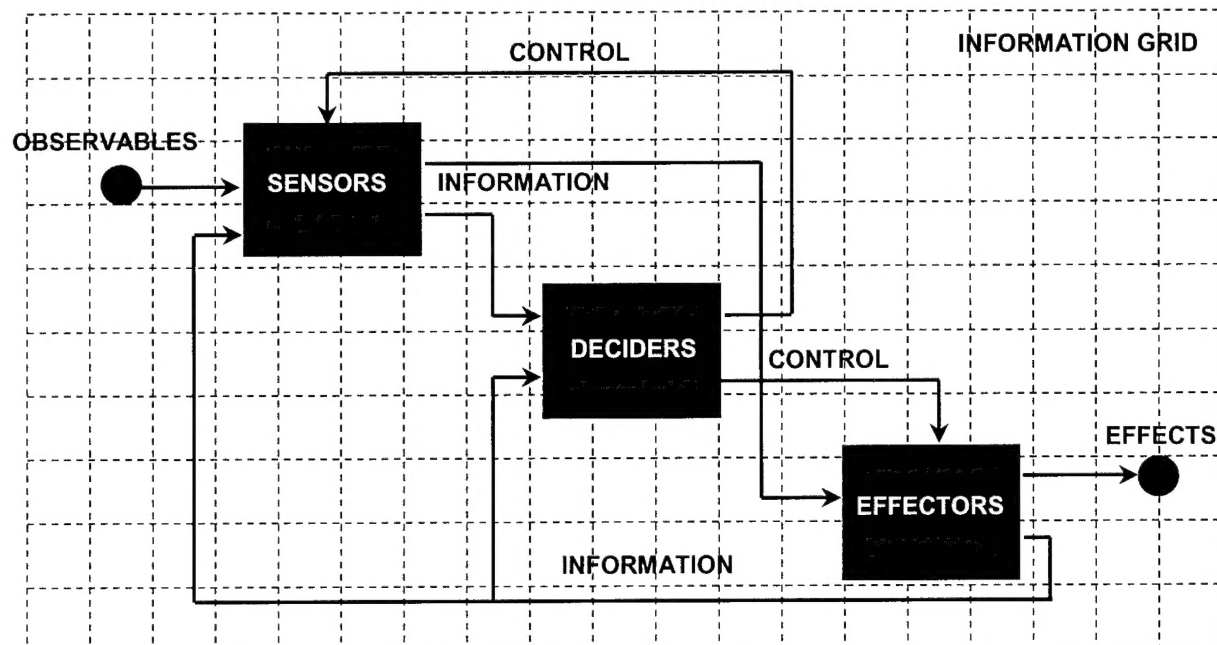

Figure 2. Logical Model of NCW by Cebrowski and Garstka[4]
(Note that sensors, deciders, and effectors are not separate, independent entities.)

ASW EXAMPLE

This section provides an example that illustrates how queueing theory can quantify NCW. It should be noted that, while this illustration makes simplifying assumptions, more complex scenarios are also amenable to analysis via queueing theory.

The scenario is a Blue submarine searching for a Red submarine in a cluttered environment. Two major factors are examined: (1) the probability of Blue detecting/classifying a Red target and (2) the mean time a contact spends on an operator's screen before the detection/classification process begins.

Whether in a platform-centric or network-centric environment, the same basic ASW functions are conducted: search, localization, and attack. During the search phase, the ASW force detects and classifies all sonar contacts. If no sonar contacts are a threat, then the

submarine declares the patrol area safe, and other units can operate in the area without fear of an enemy submarine. If any of the sonar contacts are a threat, then the threat is located and the ASW force conducts target motion analysis. Depending on the situation, the threat is either monitored or attacked.

In a platform-centric environment (where little or no information is shared between ASW assets), the possibility exists that a Blue unit could spend time investigating a false contact or a contact that is not a threat (for example, a commercial fishing vessel)—resulting in a reduction of effective search speed, wasted resources, and the possibility of not detecting the target. With network-centric capabilities, however, the information grid can provide other data about contacts detected by a Blue unit. For example, a submarine can correlate organic sensor data with radar data from another platform to determine if a sonar contact is on the surface. Thus, the searching force conserves valuable time and resources, and the probability of detecting the enemy submarine increases (see figure 3).
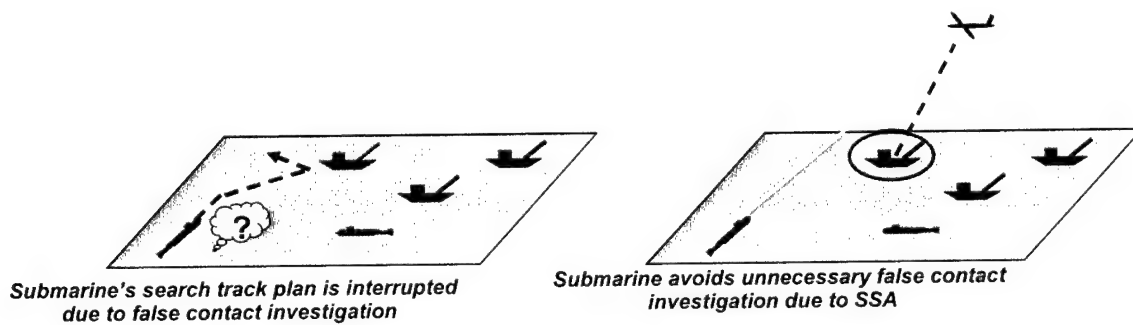

Submarine's search track plan is interrupted
due to false contact investigation

Submarine avoids unnecessary false contact
investigation due to SSA

Figure 3. Information Grid and Clutter-Reduction Concept

In this example, it is assumed that the source of clutter is the surface vessel traffic in the region that is detected by sonar. This traffic is generally composed of fishing vessels (assumed to be uniformly distributed) and merchant/tanker traffic (channeled). The vessel signatures are complex; for simplicity, it is assumed that the signals are associated with objects.

Sonar detects some of this traffic, which sonar operators must classify. The sonar operators classify most of the traffic easily and quickly as surface vessels, but a significant portion of the traffic is difficult and time consuming to classify as non-submarine because some of the attributes of the non-submarine traffic overlap those of some submarines. As a result, detection and classification queues can form in highly cluttered regions.

Balking and reneging are added complexities. Contacts pass into and out of sensor coverage. If this phenomenon occurs without detection and classification processing, then the contact has balked. If it happens within a queue, then the contact has reneged. The multicontact queueing model incorporates all of these factors. The primary output is the probability that an arbitrary contact completes detection and classification processing. The probabilities of calling a target a target (a hit or correct classification) and calling a non-target a target (a false alarm or incorrect classification) are then multipliers of the probability of acquisition.

8

As part of this research on queueing theory and ASW, the following selected network-centric concepts for improving ASW effectiveness were developed:

1. Reduce false contact loading on the ASW system by identifying contact sources through improved shared situational awareness (SSA).

2. With false contact loading reduced, lower detection thresholds to increase the probability of target detection.

3. Use collaboration with experts to improve classification performance.

4. Use agents to reduce the sea combat commander's workload.

In this example, results and analysis for the first concept are presented (work on the other three concepts is ongoing).

For all four concepts, a general formula for measuring offensive ASW effectiveness is

$$P_{ASW} = P_{DET} * P_{CLASS} * P_{LOC} * P_{ATK}, \tag{1}$$

where

P_{ASW} = probability of successfully attacking the threat before it attacks,

P_{DET} = probability of threat detection,

P_{CLASS} = probability of correct classification,

P_{LOC} = probability of successful localization to within weapon launch criteria, and

P_{ATK} = probability of successful attack, given detection, classification, and localization.

In the real world, each term in equation (1) has a queueing aspect, such as waiting time and demand for service.

In particular, this example examines P_{CLASS}, which is defined as

$$P_{CLASS} = P_{ACQ\ CLASS} * P(T \mid t), \tag{2}$$

where

$P_{ACQ\ CLASS}$ = probability that the threat acquires classification service,

$P(T|t)$ = probability of recognizing the threat contact as the actual threat,

T = threat decision, and

t = true target.

For this experiment, an exponential distribution describes the arrival time, service time (mean: 0.5 hour), and renege time (mean: 0.33 hour). The arrival rate is the rate at which a sensor operator sees new contacts, and the service rate is the rate at which a sensor operator prosecutes a given contact. The renege rate is the rate at which contacts leave detection range. In addition, a maximum queue length of 20 is assumed. The maximum queue length corresponds to the maximum number of contacts that the system of sensor operators can deal with at a time. Figure 4 shows the results.
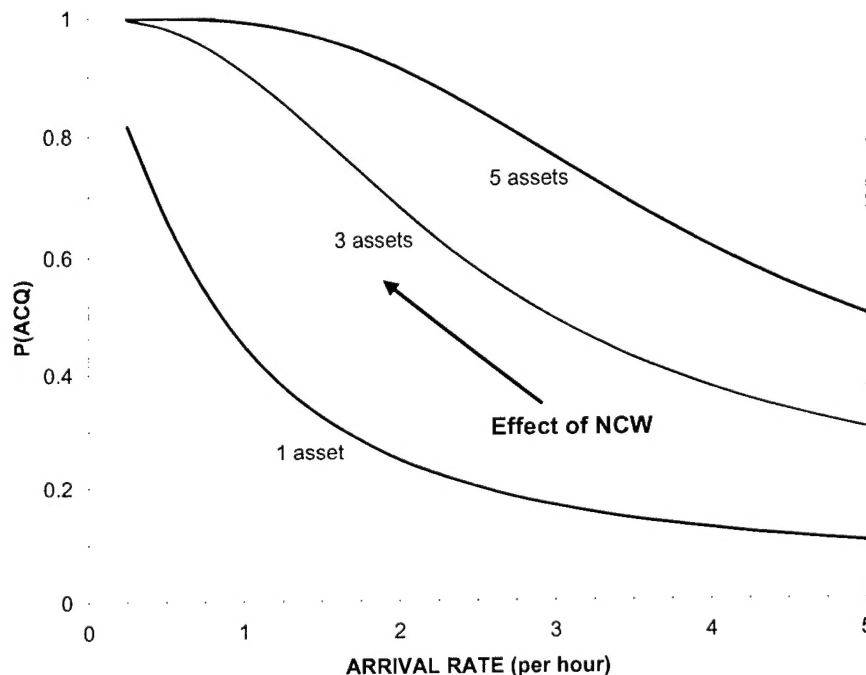

Figure 4. Probability of Investigating a Threat in a False Contact Environment

As the arrival rate decreases, the probability of acquisition increases. The primary way NCW reduces the arrival rate is by sensor fusion. Sensor correlation (both organic and non-organic) can eliminate non-submarine contacts. For example, fusing sonar and radar returns can determine if a contact is on the surface. The effect of a reduced arrival rate is independent of the number of servers (assets).

This study also examined the mean time a contact spends on the operator's screen before the detection/classification process begins (see figure 5). The key way NCW increases the number of servers working on a problem is the network grid. The implementation of the network grid allows multiple people to examine the same sensor data in real time. As the arrival rate decreases, the mean time in the queue decreases. As arrival rate increases, waiting time increases above the mean time to renege, and probability of acquisition rapidly decreases. As already discussed, the primary way NCW reduces the arrival rate is via sensor correlation.
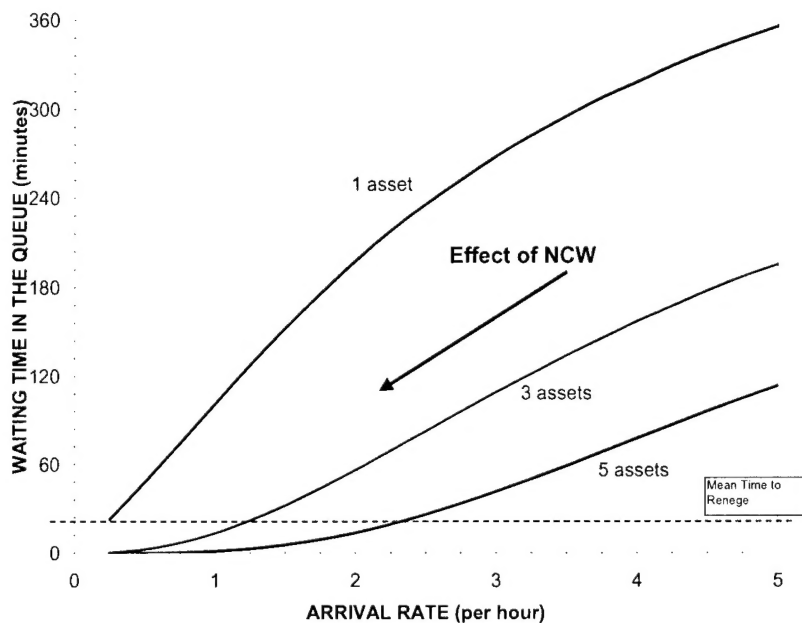
360

300

240

180

120

60

0

WAITING TIME IN THE QUEUE (minutes)

1 asset

Effect of NCW

3 assets

5 assets

Mean Time to
Renege

0   1   2   3   4   5

ARRIVAL RATE (per hour)

Figure 5. Waiting Time To Investigate a Contact

Figures 4 and 5 illustrate that decreasing the arrival rate and/or increasing the number of servers will both increase the probability of acquisition and decrease the mean waiting time in the queue. The effects are greatest (nonlinear) when both the arrival rate is reduced and the number of servers is increased. Thus, NCW offers the ability to perform quicker and more accurate detection/classification. An accurate surface picture shared among the ASW units could increase ASW success. Networking the force for information transfer is a key enabler of this aspect of SSA.

SUMMARY AND CONCLUSIONS

Because demand for service characterizes many warfare tasks, queueing theory offers an appropriate framework for understanding NCW. Other analysis techniques might prove feasible, but they require investigation. Queueing theory can show benefits of NCW accruing across sensors, shooters, and effectors. In addition, queueing theory can quantify the nonlinear force multiplier effect of NCW. Decreasing the rate of incoming information results in improved performance and higher values of warfare metrics. Increasing the number of assets working on a problem will increase effectiveness, while sharing and fusing information will allow everyone to be more aware of the battlespace.

Furthermore, queueing theory can show the benefits of NCW in three primary ways:
(1) effects of decreasing the rate of unwanted incoming information, (2) effects of increasing the number of assets working on a problem, and (3) effects of sharing and fusing information.

REFERENCES

1. D. S. Alberts, J. J. Garstka, and Frederick P. Stein, *Network Centric Warfare: Developing and Leveraging Information Superiority,* 2nd edition, Command and Control Research Program, Washington, D.C., 1999.

2. D. Gross and C. M. Harris, *Fundamentals of Queueing Theory*, 3rd edition, John Wiley & Sons Inc., New York, 1998.

3. K. M. Sullivan and I. Grivell, "QSIM: A Queueing Theory Model with Various Probability Distribution Functions, NUWC-NPT Technical Document 11418, Naval Undersea Warfare Center Division, Newport, RI, 14 March 2003.

4. A. K. Cebrowski and J. J. Garstka, "Network Centric Warfare: Its Origin and Future," *Naval Proceedings*, January 1998, pp. 28-35.

BIBLIOGRAPHY

Allen, A. O., *Probability, Statistics, and Queueing Theory with Computer Science Applications,* 2nd edition, Academic Press Inc., Boston, MA, 1990.

Ancker, C. J., and A. V. Gafarian, "Queueing with Impatient Customers Who Leave at Random," *The Journal of Industrial Engineering,* vol. 13, 1962, pp. 84-90.

Ancker, C. J., and A. V. Gafarian, "Queuing with Reneging and Multiple Heterogeneous Servers," *Naval Research Logistics Quarterly,* vol. 10, 1963, pp. 125–149.

Ancker, C. J., and A. V. Gafarian, "Some Queuing Problems with Balking and Reneging I," *Operations Research,* vol. 11, 1963, pp. 88-100.

Ancker, C. J., and A. V. Gafarian, "Some Queuing Problems with Balking and Reneging II," *Operations Research,* vol. 11, 1963, pp. 928-937.

Hazen, M., B. Burton, R. Klingbeil, K. Sullivan, M. Fewell, I. Grivell, C. Philip, and P. Marland, "The Analysis of Network-Centric Maritime Interdiction Operations (MIO) Using Queueing Theory," 8th International Command and Control Research and Technology Symposium, Washington, DC, June 2003.

Klingbeil, R., and K. Sullivan, "An Analysis of Decision-Making Time Delay," NUWC-NPT Technical Memo 03-028, Naval Undersea Warfare Center Division, Newport, RI, 10 February 2003.

INITIAL DISTRIBUTION LIST

Addressee	No. of Copies
SPAWAR Systems Center, San Diego, CA (G. Galdorisi)	1
Defense Technical Information Center	2
Center for Naval Analyses (B. McCue)	1
Chief of Naval Operations (N61F (R. O'Conner, M. Bell), N74 (CDR R. Snook))	3
Naval Network Warfare Command (P. Jackson)	1
Naval War College (T. Choinski)	1
Naval Warfare Development Command (W. Perras, J. Miller, LCDR D. Koczela)	3
Surface Warfare Development Group (CAPT J. Natale)	1
Fleet Forces Command (J. Barkley)	1
Defence Science and Technology Organisation, Rockingham, Western Australia (C. Davis)	1
Defence Science and Technology Organisation, Ministry of Defence, Edinburgh, Australia (M. Fewel, I. Grivell)	2
Defence Research and Development Canada, Dartmouth, Nova Scotia, Canada (M. Hazen)	1
Maritime Operational Research Team National Defence Headquarters, Ottawa, Ontario, Canada (R. Burton)	1
Maritime Systems Group, Defense Technology Agency, Her Majesty's New Zealand Naval Base, Auckland, New Zealand (S. McMillan)	1
Defence Science and Technology Laboratory, Portland, United Kingdom (P. Marland)	1